Design of the Experimental Procedures for Analysis of Thermal and Electrical Properties of a Prismatic LiFeYPO4 Battery in a Modified Electric Car

Chayangkun Sanguanwatana, Chadchai Srisurangkul, Monsak Pimsarn and Shoji Tsushima

Abstract As being the most important part in the energy supply system, the battery must be carefully monitored in order to optimize the performance and to prolong its life. The most affected parameter to the battery is the operating temperature as the higher operating temperature increase the performance but shorten the life and with lower operating temperature can ensure longer life but reduce the performance. With this, the battery thermal management system is created in order to keep the operating temperature at the suitable range. In order to achieve this, thermal behaviour in loaded condition must be analysed beforehand. A series of experimental procedures is designed for the selected lithium iron phosphate battery to determine the thermal properties such as heat capacity, heat generation, and cell temperature according to the electrical load applied. Derived thermal model of lithium ion battery was utilized for this purpose as it shows the relationship between the thermal, electrical properties and other parameters such as voltage, current and cell temperature. When the battery is applied with electrical load, the data of voltage, current, and surface cell temperature can be used to determine the thermal properties and at the same time, electrical properties such as open circuit voltage, state of charge and internal resistance are also obtained for the performance evaluation.

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C. Sanguanwatana (✉) · C. Srisurangkul
Automotive Laboratory, National Metal and Materials Technology Center, Bangkok, Thailand
e-mail: aura_win@hotmail.com

M. Pimsarn
King Mongkut's Institute of Technology Ladkrabang, Bangkok, Thailand

S. Tsushima
Research Center for Carbon Recycling and Energy, Tokyo Institute of Technology, Tokyo, Japan

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1 Introduction

Electric vehicle has become one of the alternatives for replacing the fossil-fuel vehicle due to the rapid decrease in the energy source and increase in the automobile utilization. Also, with the zero pipe-tail emission, the replacement of electric vehicle can decrease a great deal of the amount of green house gas released into the earth's atmosphere. National Metal and Materials Technology Center, Thailand (MTEC) joined with Electricity Generating Authority of Thailand (EGAT) in order to form the electric car project modified from the conventional gasoline powered car. This has the conventional components replaced with the electrical ones such as motor and batteries. The benefits from this includes the reduced cost of purchasing a brand new electric car and this can demonstrate that in the future, used gasoline cars can be modified into electric cars which is a merit in terms of materials recycling.

Many tests are required in order to maximize the performance of the vehicle. In this paper, the main focus is put on the battery which is the most important component in the power supply system. With the proper design of battery management system, the performance of the battery can be maximized. Also, it is known that the greatest enemy of the battery is heat because heat is the main factor which impacts the battery's performance directly.

The sudden change in temperature can change the form of active chemicals in the battery. This result in many serious consequences depends on the temperature level. Extremely low operating temperature can cause lithium plating while charging the battery. On the other hand extremely high operating temperature can build up the pressure due to gassing inside the cell, cathode material breakdown and possibly thermal runaway. To keep the suitable operating temperature, battery thermal management system or in short BTMS can be a great help. BTMS is the system which monitors the battery temperature, provide the battery with the proper cooling system in order to prolong battery's life and maximize its performance. However, before the design of BTMS, it is best to understand the thermal behavior of the selected battery or to perform thermal characterization of the battery. This includes the determination of thermal properties of the battery which includes heat capacity and heat generation while the battery is loaded. As different amount of load is applied to the battery, it is expected to see the different results of thermal properties with different electrical load. With the data of thermal properties of the battery, thermal characterization can be performed to see the change in cell temperature and then BTMS can be designed based on those results.

Table 1 Characteristics of several types of lithium ion batteries [1]

Cathode material	Typical voltage (V)	Energy density		Thermal stability
		Gravimeric (Wh/Kg)	Volumetric (Wh/L)	
Cobalt oxide	3.7	195	560	Poor
Nickel cobalt aluminum oxide (NCA)	3.6	220	600	Fair
Nickel cobalt manganese oxide (NCM)	3.6	205	580	Fair
Manganese oxide (Spinel)	3.9	150	420	Good
Iron phosphate (LFP)	3.2	90–130	333	Very Good

2 Lithium Iron Phosphate Battery

As known that lithium ion battery contains many attributes which has a lot of advantages over the other types of battery such as higher working voltage comparing to aqueous batteries, less self-discharge rate, higher energy density and contains no memory effect. With this, it was selected to be used for the modified electric car. The cell chemistry of the battery is "lithium iron yttrium phosphate" which has additional advantages comparing to the other types of lithium ion batteries. This includes the long life span, great thermal stability and less impact to the environment comparing to the cobalt cells. With great thermal stability, it becomes the safest lithium ion battery type because under the situation where the battery is misused such as in a very hot environment, lithium iron phosphate battery will not decompose at high temperature.

From Table 1, it can be seen that even though the operating voltage of lithium iron phosphate battery is the lowest among the others, the (thermal) stability is the best. As invented by John Goodenough's research group at the University of Texas in 1996 [2], it gradually became popular and is utilized many applications such as One Laptop per Child Program in China, Solar Powered Path Lights and many electrical-converted vehicle projects.

3 Battery Thermal Safety Issues and Thermal Management System

Abusive or uncontrolled use of a battery can lead to serious consequences. Cell voltage and operating temperature are the most affected parameters towards the failure of lithium batteries. It is needed to be controlled at some range. Figure 1 shows the safe area for using lithium ion cell.

From Fig. 1, it shows that many consequences from several abusive situation (dealing with voltage and temperature). This means that the user have to maintain the suitable range of operating voltage and temperature at the same time. For example, if the battery is used at room temperature but the battery was

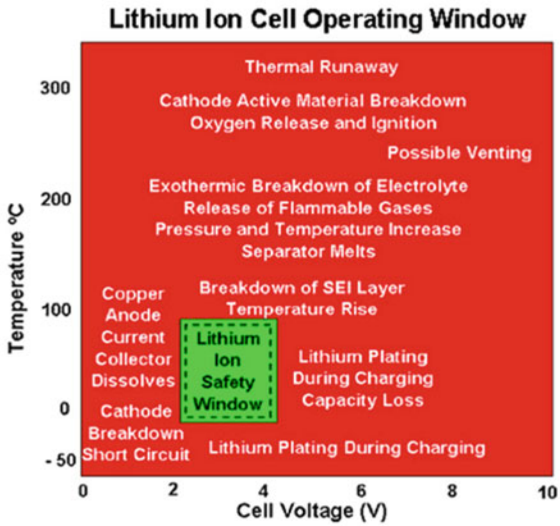

Fig. 1 Lithium ion cell operating window [3]

overcharged (overvoltage), it may result in lithium plating which permanently reduce the capacity. Or if the voltage is at 3.3 V but the operating temperature is well over 100 °C, it will surely melts the separator inside the cell and short circuit the whole system. Thermal runaway is the most severe consequences which could ever happen because it can lead to the explosion of the battery.

At this point, the consequences of using the battery outside the temperature range can be more severe than using it outside the voltage range as it will not only damage the battery but also damage the user. Therefore, it is important that the operating temperature is kept at the optimized range.

Battery Thermal Management System (BTMS) is therefore designed for this purpose. It can be used to observe and regulate the temperature not to exceed the limit. This can help prolonging the life of the battery, maximize the performance and also ensure the highest degree of safety of the user. However, some procedures are needed before the construction of BTMS. According to NREL, following issues are to be discussed: cell characteristics, module cooling strategy, operating conditions and battery thermal responses.

In this case, the battery thermal response is the main focus. Various tools can be used in the development of the battery thermal management system. This includes thermal analysis (CAD), fluid and heat transfer experiments and simulations (CFD), thermal characterization and vehicle testing [4] (Fig. 2).

An amount of work has been done in order to see how heat is transferred from the battery in the designed cooling method [5]. However, thermal properties of the battery used for this simulation is simply averaged from the data of chemistry structure of the cell in the manual from the manufacturer. To improve the accuracy of the results, thermal properties should be obtained by using thermal model of the battery.

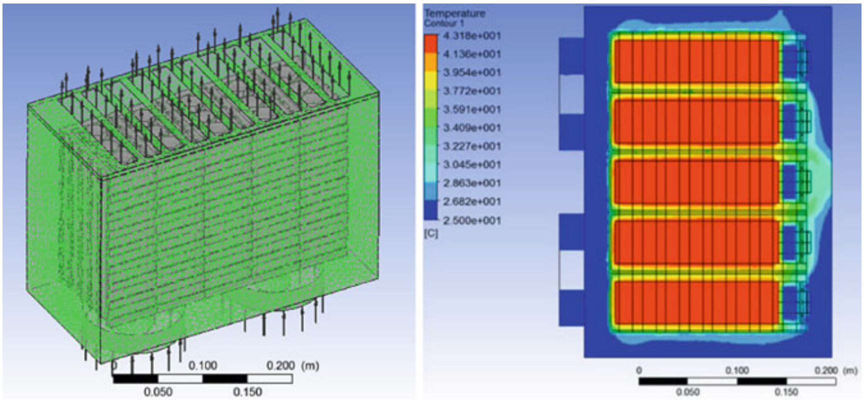

Fig. 2 Simulation of fluid and heat transfer with thermal analysis of the battery [5]

4 Battery Thermal Model

From the work of Newman et al. [6], it was found that many researchers[7, 8, 9] used the thermal model for a single cell in order to capture thermal behavior of the battery while being loaded. Few assumptions are needed for applying this model such as the uniform temperature distribution throughout the cell and stable chemical reactions. It is summarized as followed:

$$I(V_{oc} - V) + IT_{cell}\frac{\partial V_{oc}}{\partial T_{cell}} = h\left(T_{surf} - T_{amb}\right) + C_p\frac{dT}{dt} \tag{1}$$

I = Current (A), V_{oc} = Open Circuit Voltage (V), V = Cell Voltage (V)

T_{cell} = Internal Temperature (°C), T_{amb} = Ambient Temperature (°C),

T_{surf} = Surface Temperature (°C), C_p = Heat Capacity (J/ °C), h = Surrounding heat coefficient (W/ °C)

This equation is a result of a heat balance which considering the battery as a control volume. It can be seen that there are two terms on the left hand side. The first term is the overpotential resistance term which results from the electrical power applied, it is always positive. The second terms deal with the chemical reaction in the cell, the charge and discharge reaction can result in endothermic and exothermic condition for the battery respectively in which it can be related to the enthalpy change and Gibb's free energy. This second term on the left hand side is usually called the reversible entropic term and it can either positive or negative.

As for the right hand side, the first term represents the heat transfer from the battery to the surroundings, it can also be considered in terms of the difference between the cell surface and the ambient temperature. Surrounding heat transfer coefficient, h will also be one of the properties to be investigated before the calculations of heat capacity C_p. In the second term on the right hand side, heat capacity represents the amount of heat required for changing the temperature of the battery. It is the main focus for this research work.

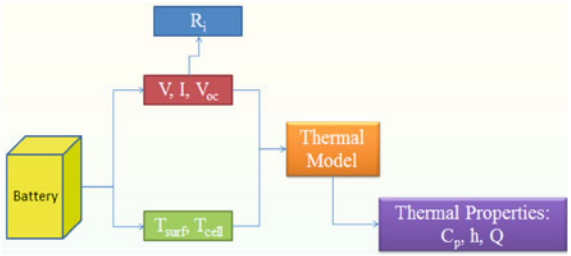

Fig. 3 Block diagram shows overall picture of this research work

5 Design of the Experimental Procedures

The main objective of this work is to determine thermal properties of the selected Li-ion battery at different loads and thermal environments. To simplify the procedures, the block diagram below shows the overall picture of this work. The main objective of this work is to determine thermal properties of the selected Li-ion battery at different loads and thermal environments. To simplify the procedures, the block diagram below shows the overall picture of this work.

As illustrated in Fig. 3, to serve the main purpose of this work, it is needed to design the procedures in order to obtain the voltage and current load data while the battery is loaded and at the same time surface and cell temperature are also monitored. This is based on the thermal model shown in the previous section which requires those data in order to determine thermal properties of the battery. Furthermore, R_i or internal resistance is included for evaluating the battery's performance and is calculated from the data of voltage and current load.

From Fig. 4, a selected battery is connected to the electronic load/power supply with thermocouple probe attached to the surface and infrared temperature sensor attached at the top of the cell in order to measure the internal temperature. The electronic load and power supply are used for discharging and charging the battery respectively. The infrared thermal sensor for measuring the cell internal temperature. Thermocouple cannot be used for measuring internal temperature is because it is required to contact the core of the cell which can lead to short circuit. Therefore, using the non-contact measurement is more suitable. The small blue box represents the Data Acquisition tool where it is used for recording the temperature measured at the surface and the cell. A computer is used for storing the experimental data for the analysis. The transparent purple box is the thermal chamber where it will be used for regulating the environmental temperature around the battery, this deals with the temperature coefficient which will be explained in the next section.

The selected lithium ion battery is the Thunder Sky lithium iron phosphate battery with the capacity of 60 Ah. Specifications are shown below (Fig. 5) (Table 2):

The design of experimental procedures is based on the thermal model of the battery and also the specifications of the battery. The procedures are divided into two main parts:

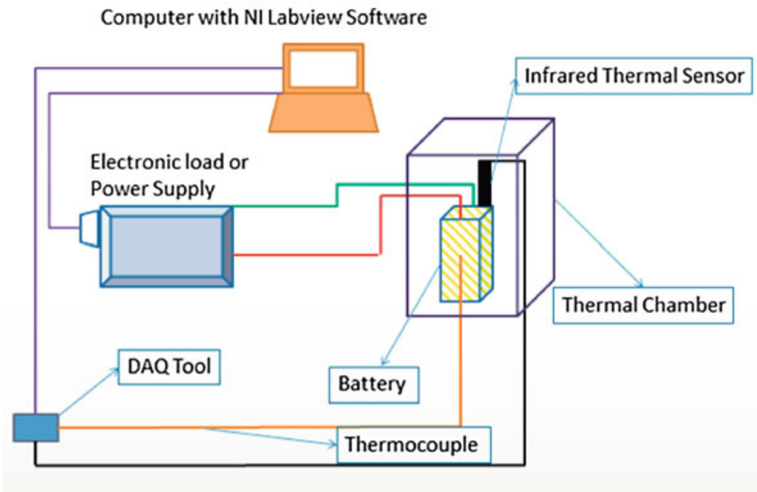

Fig. 4 Schematic diagram for the experimental setup

1. Determination of heat generated from the cell
2. Calculations of thermal properties of the cell

In the first part, the heat generated from the cell is the combination of all terms on the left hand side in Eq. 1. This can be obtained from recording the voltage, current and cell temperature while the battery is being charged or discharged. The main parameter here is the current load applied (I), which can be 1 CA. 0.5 CA or 2 CA (Fig. 6).

However, in the second term, dV/dT or the temperature coefficient is present. This has to be determined in a separated experiment. See figure below for illustrations (Fig. 7):

The battery is put inside the adjustable temperature thermal chamber and while the environmental temperature is adjusted, the cell temperature and open circuit voltage will be observed and recorded. This will be used for the calculation of temperature coefficient.

In the second part, when the battery is charged or discharged and the voltage, current and temperature data are gathered, thermal properties can be determined. From Eq. 1 it can be seen that there are two variables to be determine. They are heat capacity (C_p) and surrounding heat transfer coefficient (h).

With the steady state condition, where the cell temperature stay constant with time ($\partial T_{cell}/\partial t = 0$), the term with heat capacity will be eliminated and thus, surrounding heat transfer coefficient (h) can be determined and while this depends on the current load applied to the battery, I (and also the heat generated, Q). Therefore, when surrounding heat coefficient is determined, it can be applied in the transient condition ($\partial T_{cell}/\partial t \neq 0$) to find the heat capacity of the battery.

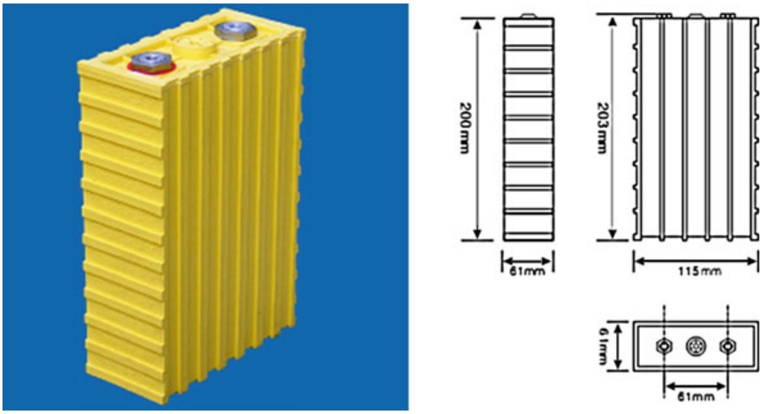

Fig. 5 The selected battery for the experiment [10]

Table 2 Specifications of the selected battery for the experiment [10]

Model	TS-LFP60AHA
Nominal capacity	60 Ah
Operation voltage	Charge: 4.0 V, Discharge: 2.8 V
Maximum charge current	Less or equal to 3 CA
Maximum discharge current	3 CA or less for constant current 20 CA or less for impulse current
Standard charge/discharge current	0.5 CA
Cycle life	(80DOD %) $\geq$ 3,000 times (70DOD %) $\geq$ 5,000 times
Temperature durability of case	$\leq$200 °C
Operating temperature	−45 to 85 °C for both charge and discharge
Self-discharge rate	$\leq$3 % (Monthly)
Weight	2.3 kg $\pm$ 50 g

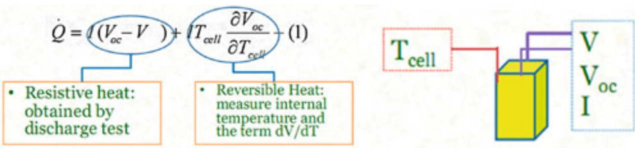

Fig. 6 Determination of heat generated from the cell

The initial condition has the 100 % charged battery stored in the room temperature. As the battery is put through the discharge test, the value of V-V_{oc} will be changed as the depth of discharge increases. Also, the cell temperature here will also be increased, then, the value of Q will be different in the different state of charges. This will also apply on surrounding heat transfer coefficient and heat

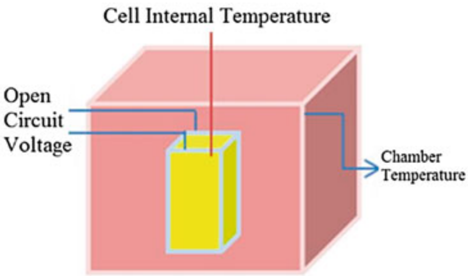

Fig. 7 Experiment for the temperature coefficient

capacity and explained in the previous paragraph. This will also include the other experiment with different amount of current load applied to see the change in the focused thermal properties.

6 Preliminary Study and Results

At this stage, performance characteristics of the battery were studied. These include the charge and discharge profile (constant and pulsed current). The surface and terminal temperature were also recorded (Fig. 8).

From the figure, the voltage response from the constant current discharge shows that it tends to be flat from 10 to 80 % depth of discharge. This is suitable for the electric vehicle application due to its voltage stability. Furthermore, the chemistry of lithium iron phosphate gives the advantage in terms of thermal stability as it is unlikely to reach the stage of thermal runaway unless is extremely abused.

From Figs. 9 and 10, the temperature response from the pulse test shows that terminal temperature is more sensitive than surface temperature because when the load is put to zero, surface temperature dropped until the load is turned back on again.

The advantages of conducting pulse current test are that more data can be obtained and the dynamic of temperature change can also be captured. In this test, open circuit voltage can be observed as used for calculating heat generation as noted in thermal model. Furthermore, the data obtained from the pulsed discharge curve can be used to calculate the internal resistance which can also estimate battery's life as shown in Fig. 11.

Note that in this test, surface temperature is only measured at two points in front of and on the side of the battery. Also, it is observed that the positive terminal gives out heat more than that of negative terminal. This concludes that positive terminal is the point of heat concentration.

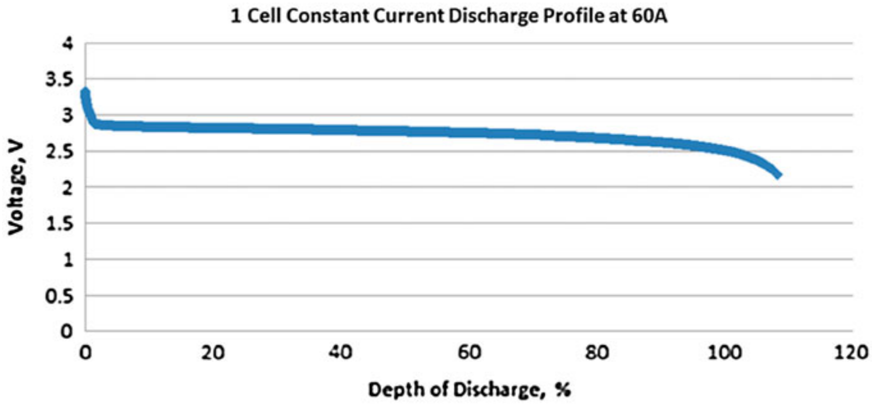

Fig. 8 Constant current discharge profile

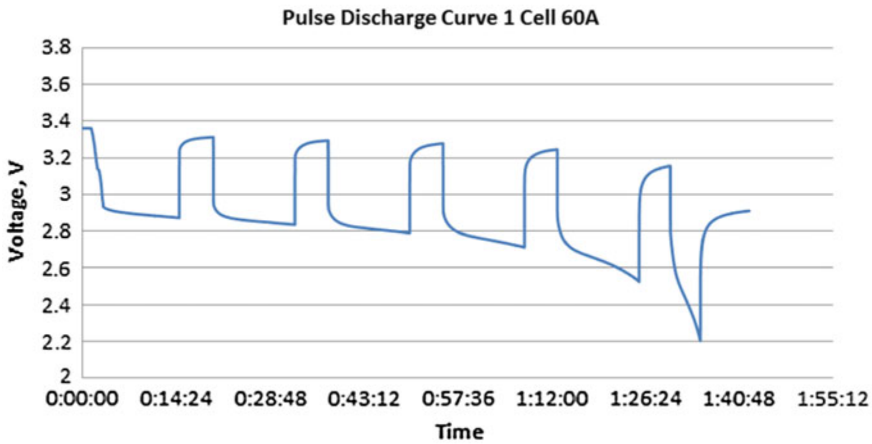

Fig. 9 Pulse discharge curve profile

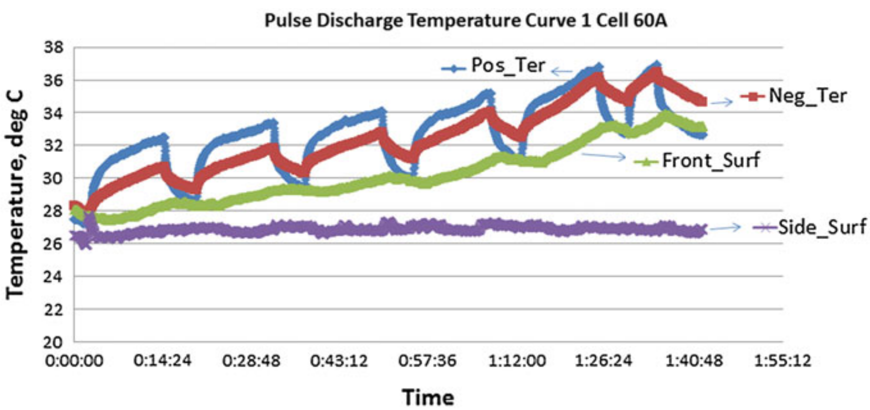

Fig. 10 Battery surface and terminal temperature response from pulse discharge test

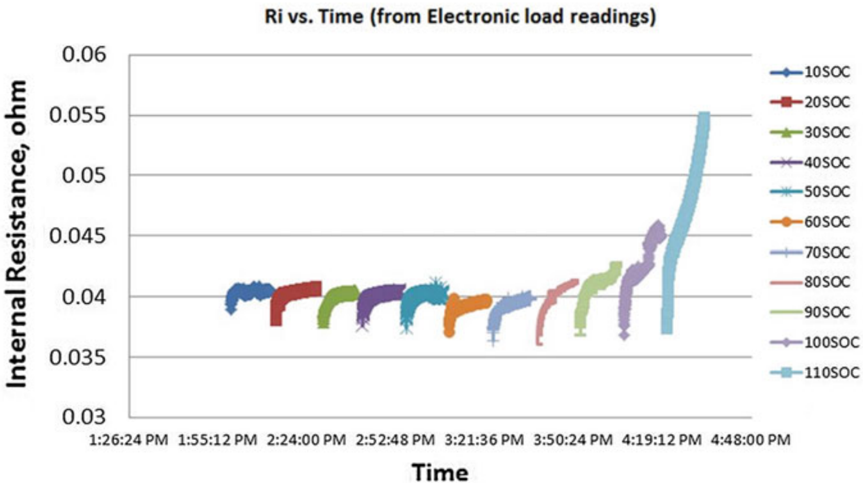

Fig. 11 Internal resistance calculated from the pulse test result (60 A)

7 Conclusions

Experimental procedures have been designed for the determination of thermal properties of the selected battery for the modified electric vehicle. Currently, the charge and discharge characteristics of the battery are obtained and in the same time surface and terminal temperature are monitored. In the next step, infrared temperature sensor will be installed at the top of the battery for internal temperature measurement. This is the main key towards the goal of this research work because the data of internal temperature of the battery can be used to calculate for thermal properties of the battery. Finally, when the data of thermal properties are obtained, it will be hand over to the design team of BTMS of the modified electric car and the cooling system of the battery.

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